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RESEARCH MEMORANDUM

ACCELERATION CHARACTERISTICS OF A TURBOJET ENGINE WITH VARIABLE-POSITION INLET GUIDE VANES

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

The acceleration characteristics of a turbojet engine equipped with variable-position inlet guide vanes were determined in an NACA altitude test chamber. During the study, maximum acceleration values for 3 engines of the same model were obtained and found to differ as much as 50 percent. Closing the inlet guide vanes increased the size of fuel step that could be put into the engine without encountering surge, and thus increased the maximum acceleration. A fuel-step size parameter was derived which permitted a generalization of acceleration for variations in engine speed, flight conditions, inlet guide vane position, fuel-step size and compressor inlet air pressure distribution. Compressor pressure ratio margin is only an approximate index of engine acceleration capability. Distorting the engine inlet pressure either radially or circumferentially lowered the maximum value of acceleration.

INTRODUCTION

A brief investigation was conducted in an NACA altitude test chamber to determine the acceleration characteristics of a modern axial-flow turbojet engine. The engine used in this investigation was equipped by the manufacturer with variable-position inlet guide vanes to improve the acceleration characteristics in the low speed range. Although the use of variable guide vanes for this purpose has been suggested by analysis (ref. 1, for example), no experimental data on the effectiveness of variable guide vanes are generally available. One of the objectives of this report is therefore to demonstrate the effectiveness of this method of improving acceleration characteristics. Other specific objectives of the study were to determine the effect of flight condition on engine acceleration, determine the reproducibility of acceleration characteristics for several production engines of the same model, and to determine the effect of inlet air distortion on the acceleration characteristics.

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A method of correlating acceleration characteristics for variations in flight condition, inlet air temperature, initial engine speed, and distorted engine inlet flow is developed.

Engine accelerations were made from several initial engine speeds for a range of altitudes from sea level to 55,000 feet, flight Mach numbers from 0 to 1.2, inlet air temperatures from +50 to -70° F, two settings of the variable inlet guide vanes, and two inlet air flow distortion patterns. The acceleration characteristics were determined from analysis of oscillograph traces, and are presented graphically. 3468

APPARATUS

The 9000 pound thrust engine used in this study had an axial-flow compressor equipped with variable inlet guide vanes. The guide vane assembly consists of 21 blades whose angle setting can be varied from 13° (open) to 43° (closed), measured from axial at the blade tip chord-line. A can-annular type combustor, a 2-stage turbine, and a fixed-area exhaust nozzle were used. For these tests the production engine control was replaced by a specially designed fuel system. This fuel system was capable of introducing step increases in fuel flow to any desired level.

The investigation was conducted in an NACA altitude test chamber shown in figure 1. Air supplied to the inlet section of the altitude chamber can be either heated or refrigerated to the desired temperature. Automatic throttling valves maintain the inlet and exhaust pressures at the desired level.

PROCEDURE

Engine accelerations were made by step increases in fuel flow with specially designed fuel systems. Fuel-step size was varied up to that which caused compressor surge at initial engine speeds between 60 and 100 percent of rated. During all accelerations, oscillograph recordings were made of the pertinent engine parameters. The study was made for the following range of variables:

(a) Altitude: sea level to 55,000 feet

(b) Flight Mach number: 0 to 1.2

(c) Inlet air temperatures: +50° to -70° F

(d) Inlet pressure distortion at rated engine speed: radial, 12 percent maximum to minimum; circumferential, 25 percent maximum to minimum.

The following parameters were continuously measured on a self-recording multiple-channel oscillograph:

1. Compressor inlet total pressure

2. Compressor discharge total pressure

3. Compressor speed

4. Exhaust gas temperature

5. Engine fuel flow

6. Engine inlet dynamic pressure

RESULTS AND DISCUSSION

A typical oscillograph trace of a surge-free engine acceleration resulting from a step increase in fuel flow is presented in figure 2. Typical acceleration data obtained from traces of this type are presented in figure 3, where acceleration is plotted as a function of engine speed for several fuel steps from the same initial speed. For a given fuel step, maximum acceleration was obtained after the engine speed increased about 100 rpm; after reaching maximum, the acceleration decreased almost linearly to zero. As fuel-step size is increased, maximum acceleration rises until sufficient fuel is added to cause compressor surge (indicated by the solid symbols). During the surge, acceleration falls to zero and rapidly recovers to a very high acceleration rate.

Effect of fuel step size and inlet guide vane on acceleration. - By cross-plotting data from several initial speeds it was possible to construct the acceleration maps shown in figure 4(a) and (b) for inlet guide vane settings open and closed, respectively. Acceleration values on these figures represent the peaks of curves such as those presented in figure 3. Contours of constant fuel-step size (above steady-state value) and compressor surge limits are shown. For both inlet guide vane settings, increasing fuel-step size results in higher maximum acceleration rates. For a given percentage increase in fuel flow above the steady-state value, somewhat higher accelerations resulted with the inlet guide vane in the open position. However, because much larger fuel steps (both in absolute values and percentage-wise) were permitted with the inlet guide vane closed before surge was encountered, as compared with the inlet guide vane open, considerably higher accelerations could be attained.

The effect of inlet guide vane setting on the maximum acceleration is shown directly in figure 5 as a function of engine speed. The peak in acceleration moves to higher engine speeds as the inlet guide vanes are opened.

Effect of flight condition on generalization. - A generalization of maximum acceleration is attempted by the application of the usual altitude correction factors (δ and θ) in figure 6. The corrected acceleration does not generalize for either variations in altitude or flight Mach number (figs. 6(a) and (b)). An increase in altitude or a decrease in flight Mach number (both lower inlet Reynolds number) results in decreased corrected values of maximum acceleration. It was previously determined that for this engine a decrease in Reynolds number lowered the fuel-flow surge line and raised the steady-state fuel requirement at a given engine speed; thus a smaller fuel step and lower maximum acceleration would be permitted at higher altitudes or lower Mach numbers. 3468

Reproducibility of engine accelerations. - During the course of this experimental study, acceleration characteristics were obtained for three engines, which afforded an opportunity to compare the reproducibility of acceleration data on different engines of a given model. The engines are designated A_1, A_2, and B_1. A_1 and A_2 are the same engine which was ultimately dismantled, inspected, and rebuilt without changing any major aerodynamic component. Engine B_1 was a spare engine of the same model. The maximum acceleration rates of these three engines are presented as functions of speed in figure 7. Maximum accelerations vary as much as 50 percent from the highest value at a speed of 6800 rpm. As a further means of comparing these engines, the steady-state and surge values of compressor pressure ratio and fuel flow are presented in figures 8 and 9, respectively. Although there is little difference in the steady-state pressure ratios or fuel flows, the surge values follow the order of the acceleration rates shown in figure 7. These data seem to indicate that acceleration characteristics of axial-flow engines may be very sensitive to changes in clearances introduced in assembly or by the accumulation of tolerance errors.

Compressor pressure ratio as acceleration index. - Compressor pressure ratio margin has been generally considered an index of engine acceleration capabilities. To determine the validity of this index, an attempt was made to correlate maximum acceleration as a function of this parameter. Acceleration data for 3 engines at several engine speeds and 2 inlet guide vane settings are plotted as functions of compressor pressure ratio margin in figure 10. For inlet guide vanes open there is a tendency for higher pressure ratio margins to result in higher accelerations. However, there is no consistent effect of changing engine speed. In addition, with the inlet guide vanes closed, an increase in engine speed and pressure ratio margin produces little or no change in acceleration rate. Thus, it is seen that compressor pressure ratio margin is no more than an approximate index of engine acceleration capability.

Fuel-step parameter as acceleration index. - By equating the engine acceleration to the difference between turbine power and compressor power, and making certain simplifying assumptions, the following expression for acceleration was derived (see appendix B):

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$$\dot{N} \propto \Delta W_F/N$$

The engine acceleration is proportional to the ratio of fuel step size divided by the engine speed. The acceleration data presented in figure 10 for the three engines, were plotted in figure 11 as a function of the corrected fuel-step parameter $\Delta W_F/N\delta$. The points on this figure represent the maximum acceleration rate for surge-limited fuel steps. Data for the three engines over a range of speeds and at two inlet guide vane positions define an approximate linear relation with the fuel-step parameter. The maximum deviation of the data from the curve is about ±5 percent which is within the accuracy of reading the values of acceleration from the oscillograph traces. The minimum speed considered for inlet guide vanes open operation is 6800 rpm because the inlet guide vanes are scheduled to the closed position at lower speeds. As a further check of the fuel-step parameter, acceleration data for a wide range of altitudes, Mach numbers, and inlet temperatures are shown in figure 12. The variations in inlet conditions are generalized when corrected acceleration is plotted as a function of $\Delta W_F/N\delta$.

The question arises as to how accelerations are affected when fuel steps smaller than required to cause surge are used. Accelerations for a series of fuel-step sizes up to the surge-limited values are presented as a function of the fuel-step parameter in figure 13. The data generalize consistently to the same curve obtained for variations in inlet conditions and engines (fig. 12). To permit computation of acceleration time for any acceleration path in the area between the steady-state operating line and the surge limit, data are required for acceleration rates less than the maximum. Thus, the data for the negative slope portion of curves such as shown in figure 3 are presented in figure 14 as a function of the fuel-step parameter. These data which were obtained for two engines and several fuel steps correlate in the same manner as the maximum acceleration values shown on the preceding curves. The positive slope portion of the acceleration histories shown in figure 3, which includes combustion lag and fuel-step dead time has not been considered.

Acceleration with inlet air distortion. - During the study of the subject engine, obstructions were placed at the engine inlet to determine the effects of inlet air pressure distortion on the performance and operational characteristics of the engine. Maximum accelerations with and without inlet air distortion are shown in figure 15. At a speed of 7000 rpm, distorting the flow either radially or circumferentially reduced the maximum acceleration about 17 percent. Inlet distortions likewise reduced both the surge fuel-flow and compressor pressure ratio lines presented in figures 16 and 17, respectively, thereby accounting for the decrease in maximum acceleration. The acceleration data for the inlet air flow distortions were then plotted as a function of the fuel-step parameter in figure 18. Variations in engine speed with each inlet air pattern correlate with the fuel-step parameter as with the previously presented data. 3468

CONCLUDING REMARKS

The acceleration characteristics of a turbojet engine equipped with variable-position inlet guide vanes have been studied in an NACA altitude test chamber. Distorting the engine inlet pressure either radially or circumferentially lowered the value of maximum acceleration. The maximum acceleration values as limited by compressor surge for three engines of the same model were found to differ by as much as 50 percent; nevertheless, the maximum accelerations of the three engines correlated as a function of the fuel-step size parameter. Engine acceleration increased with fuel-step size until compressor surge was encountered. Compressor pressure ratio margin was found to be only an approximate indication of acceleration capability. Closing the inlet guide vanes raised the surge-limited fuel flow and thus increased the maximum acceleration. Decreasing the inlet Reynolds number lowered the fuel margin available for acceleration and thus the maximum corrected acceleration.

A fuel-step size parameter was derived which permitted a generalization of acceleration for variations in engine speed, flight conditions, inlet guide vane position, fuel-step size, and inlet air distortion.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 11, 1954

APPENDIX A

SYMBOLS

The following symbols are used in this report:

C_p	specific heat of gas at constant pressure, Btu/lb-$^{\circ}$R
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IGV	inlet guide vane
K	constant containing rotor inertia
K_1	assumed constant, $1-T_4/T_3$
$K_2 f(c_p)$	relates fuel-air ratio to combustion temperature rise; K_2, constant; $f(c_p)$ accounts for C_p changes with temperature
N	engine speed, rpm
$\dot{N}$	engine rotor acceleration, rpm/sec
P	total pressure, lb/sq ft abs
p	static pressure, lb/sq ft abs
W_a	air flow, lb/sec
W_f	fuel flow, lb/hr
ΔW_f	fuel step above steady-state requirements, lb/hr
γ	ratio of specific heats for gases
δ	ratio of absolute compressor-inlet total pressure to absolute static pressure of NACA standard atmosphere at sea level
η_b	combustion efficiency
η_c	compressor efficiency
θ	ratio of absolute compressor-inlet total temperature to absolute static temperature of NACA standard atmosphere at sea level

Subscripts:

a	air
b	burner
c	compressor
f	fuel
ss	steady state
T	transient
t	turbine
1	compressor inlet
2	compressor outlet
3	turbine inlet
4	turbine outlet

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APPENDIX B

DERIVATION OF AN EXPRESSION FOR THE ROTOR ACCELERATION OF A TURBOJET ENGINE ACCOMPANYING A STEP INCREASE IN FUEL FLOW

Turbine power is

$$c_{p_t}\, W_a\left(1+\frac{W_f}{W_a}\right)T_3\left(1-\frac{T_4}{T_3}\right)$$

Assuming constant turbine temperature ratio (unpublished data have established this) and writing

$$T_3 = T_2 + \Delta T_b = \frac{T_1}{\eta_c}\left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1 + \eta_c\right] + \eta_b K_2 f(c_p)\,\frac{W_f}{W_a}$$

then turbine power becomes

$$c_{p_t}\, W_a\left(1+\frac{W_f}{W_a}\right)K_1\left[\eta_b K_2 f(c_p)\,\frac{W_f}{W_a} + \frac{T_1}{\eta_c}\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}\right]$$

Compressor power is

$$\frac{c_{p_c}\, W_a\, T_1}{\eta_c}\left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

Acceleration can be written as

$$\dot{N} = \frac{K}{N}\left[\left(\begin{matrix}\text{transient}\\ \text{turbine}\\ \text{power}\end{matrix} - \begin{matrix}\text{steady-state}\\ \text{turbine}\\ \text{power}\end{matrix}\right) - \left(\begin{matrix}\text{transient}\\ \text{compressor}\\ \text{power}\end{matrix} - \begin{matrix}\text{steady-state}\\ \text{compressor}\\ \text{power}\end{matrix}\right)\right]$$

[redacted]

Substitution and rearrangement of terms gives

$$\dot{N} = \frac{KK_1K_2f(c_p)}{N}\left[W_{f_T}\left(1+\frac{W_f}{W_a}\right)_T \eta_{b_T} c_{p_{t_T}} - W_{f_S}\left(1+\frac{W_f}{W_a}\right)_S \eta_{b_S} c_{p_{t_S}}\right] +$$

$$\frac{KW_{a_T}T_1}{N\eta_{c_T}}\left\{K_1 c_{p_{t_T}}\left(1+\frac{W_f}{W_a}\right)_T\left[\left(\frac{P_2}{P_1}\right)_T^{\frac{\gamma-1}{\gamma}} - 1 + \eta_{c_T}\right] - c_{p_c}\left[\left(\frac{P_2}{P_1}\right)_T^{\frac{\gamma-1}{\gamma}} - 1\right]\right\} -$$

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$$\frac{KW_{a_S}T_1}{N\eta_{c_S}}\left\{K_1 c_{p_{t_S}}\left(1+\frac{W_f}{W_a}\right)_S\left[\left(\frac{P_2}{P_1}\right)_S^{\frac{\gamma-1}{\gamma}} - 1 + \eta_{c_S}\right] - c_{p_c}\left[\left(\frac{P_2}{P_1}\right)_S^{\frac{\gamma-1}{\gamma}} - 1\right]\right\}$$

In an attempt to find a simple parameter that would be indicative of engine acceleration, typical numerical values were substituted in the above equation for several engine speeds. Assuming no changes between steady-state and transient η_c and η_b, it was found that the last two terms on the right hand side of the equation always contributed less than 10 percent to the acceleration rate. Therefore, since the first term is the determining factor of acceleration rate, simplification leads to the following expression:

$$\dot{N} \propto \frac{W_{F_T} - W_{F_S}}{N} = \frac{\Delta W_F}{N}$$

REFERENCE

1. Benser, William A.: Analysis of Part-Speed Operation for High-Pressure-Ratio Multistage Axial-Flow Compressors. NACA RM E53I15, 1953.

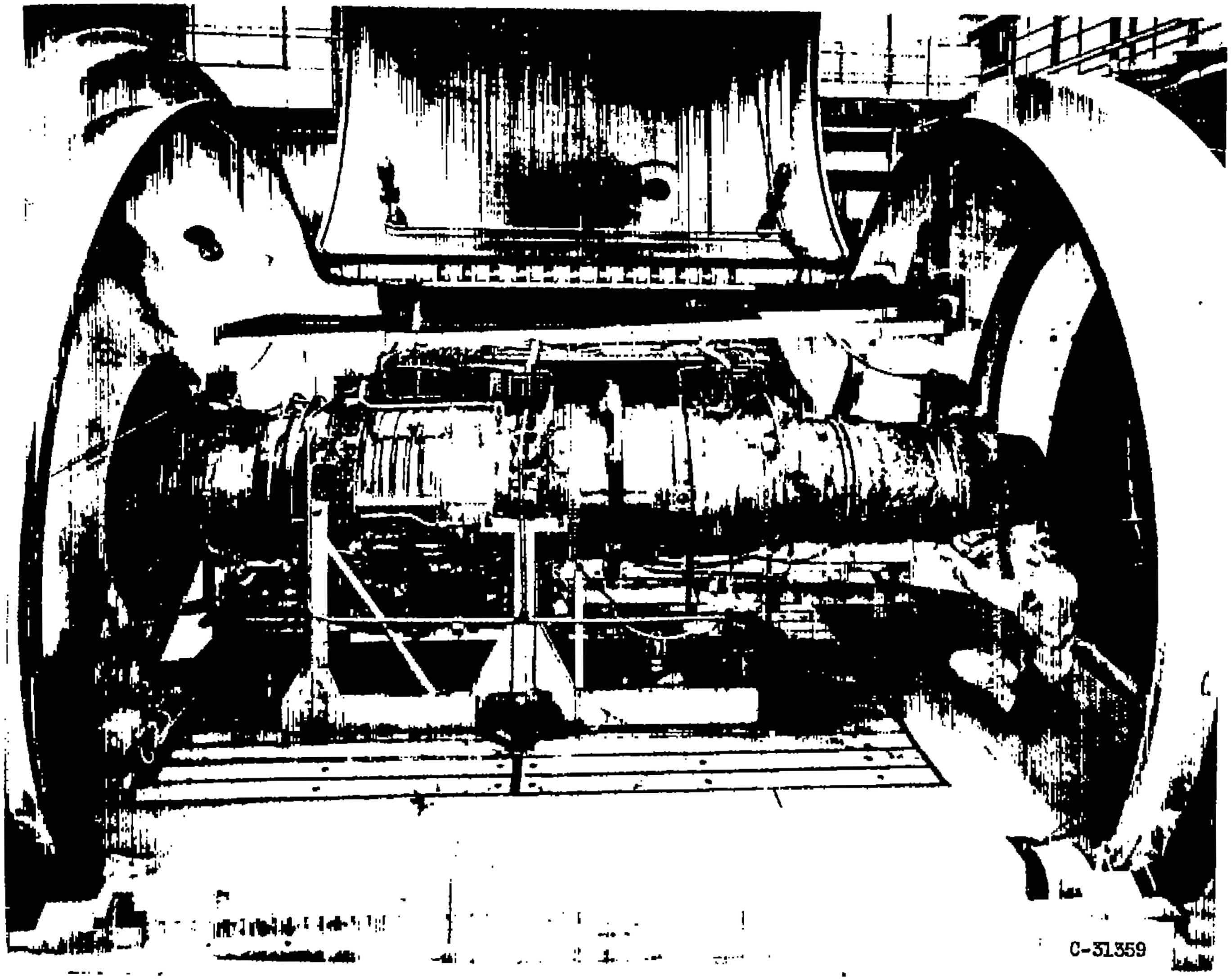

Figure 1. - Turbojet installation in altitude chamber.

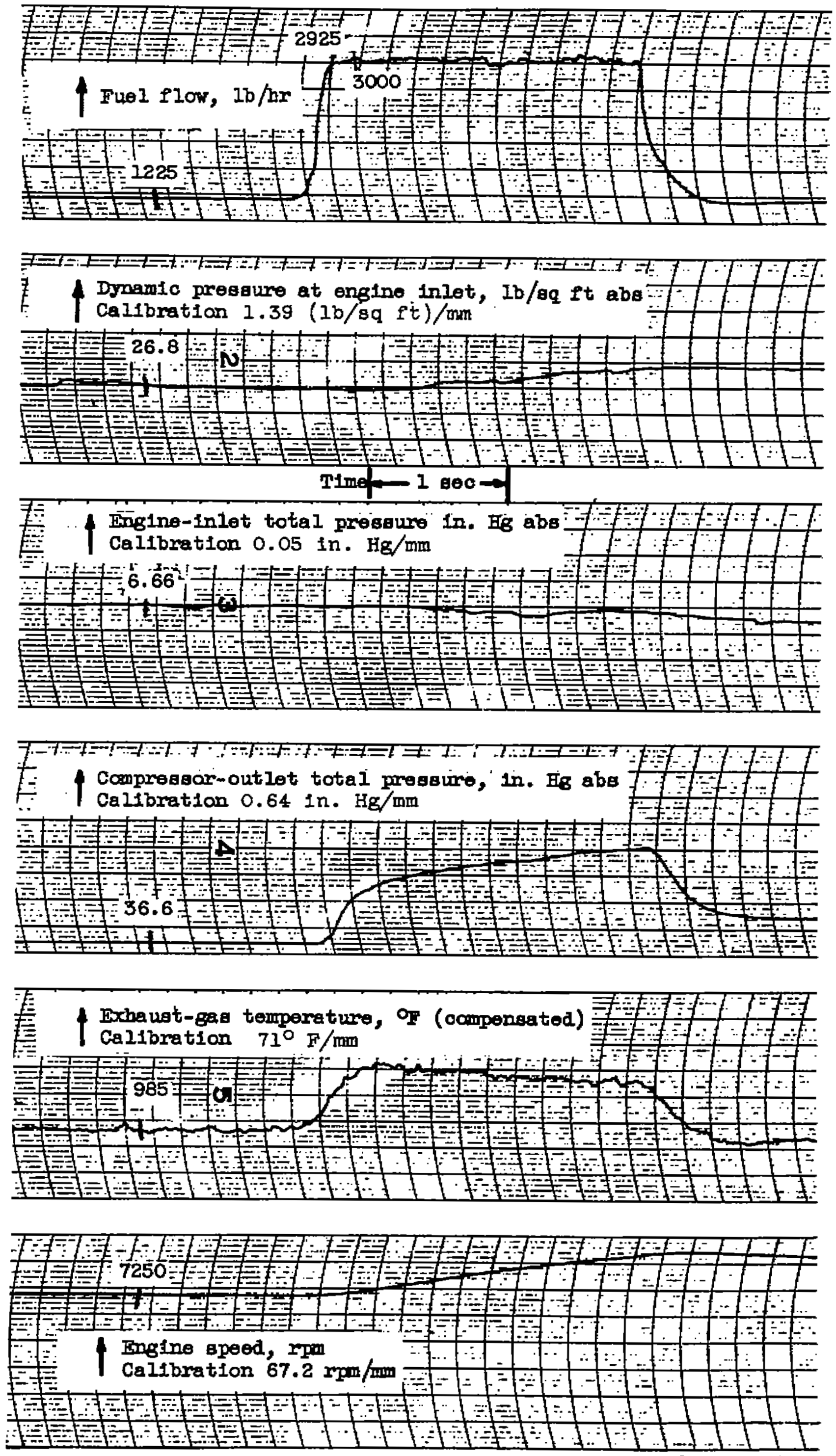

Figure 2. - Typical oscillograph trace showing measured parameters.

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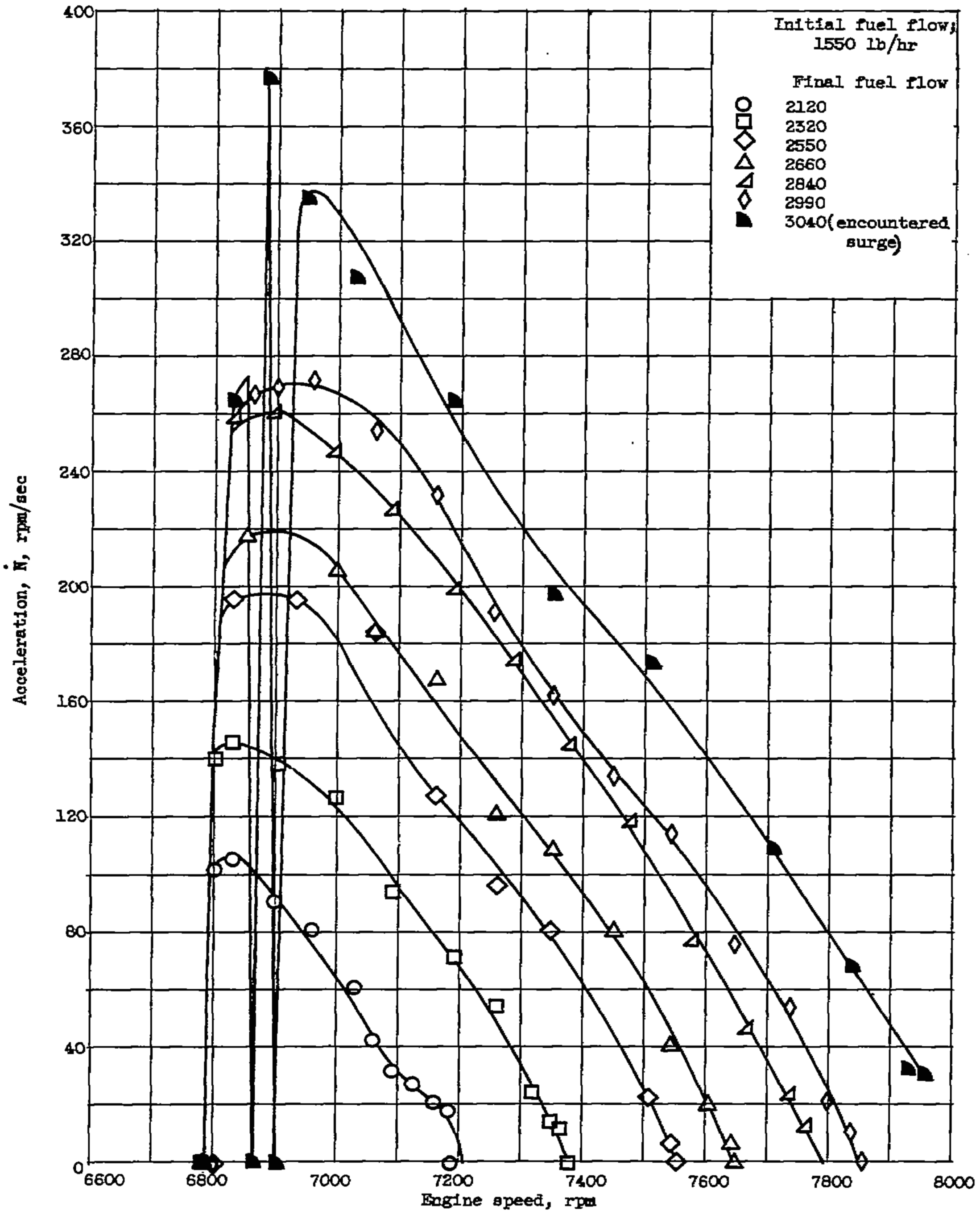

Figure 3. - Acceleration histories from same initial speed with increasing fuel steps to compressor surge. I.G.V. open. Altitude, 35,000 ft; Flight Mach number, 0.8.

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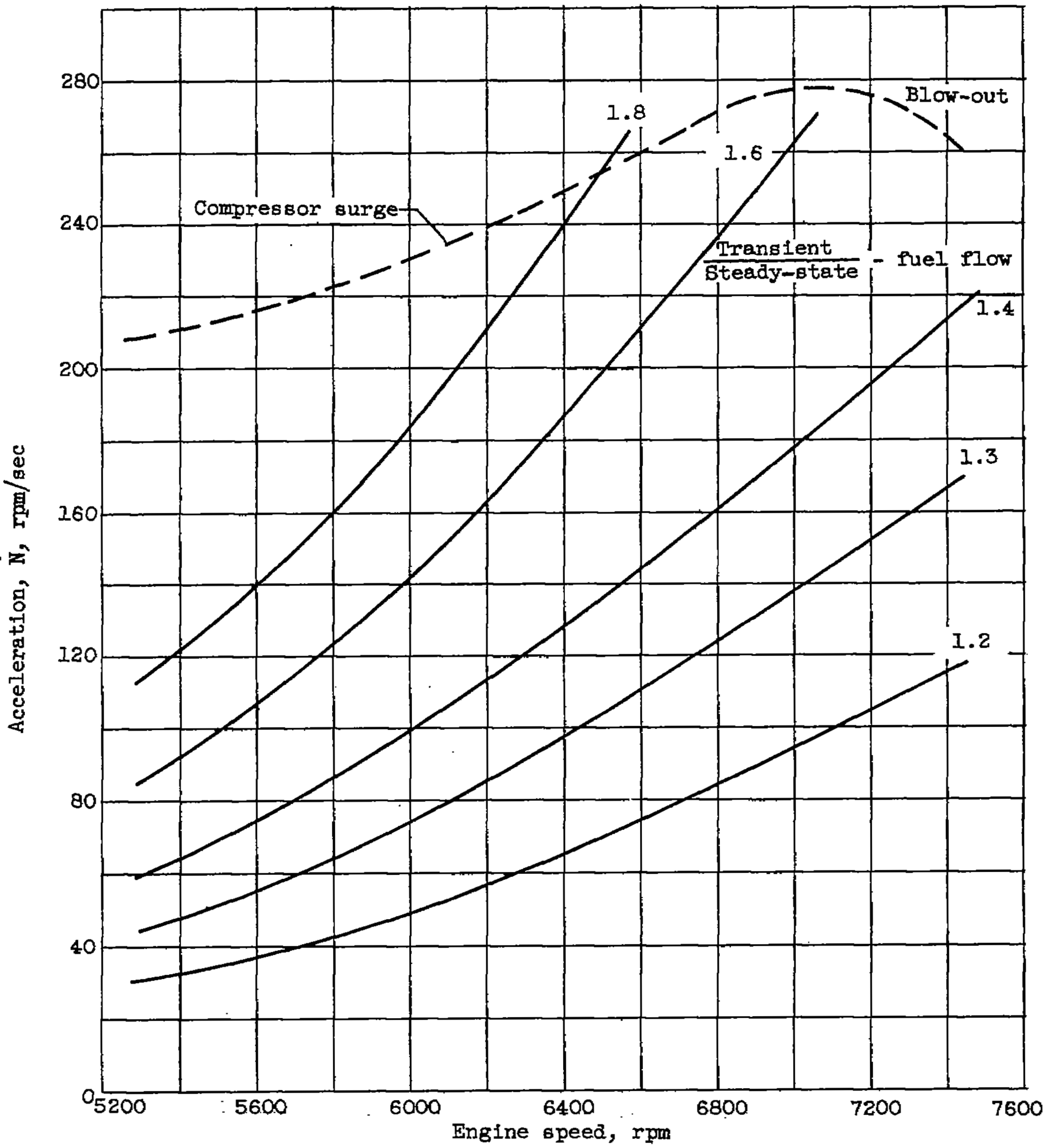

(a) Inlet guide vanes open.

Figure 4. - Effect of fuel step size on engine acceleration. Altitude, 35,000 ft; flight Mach number. 0.8.

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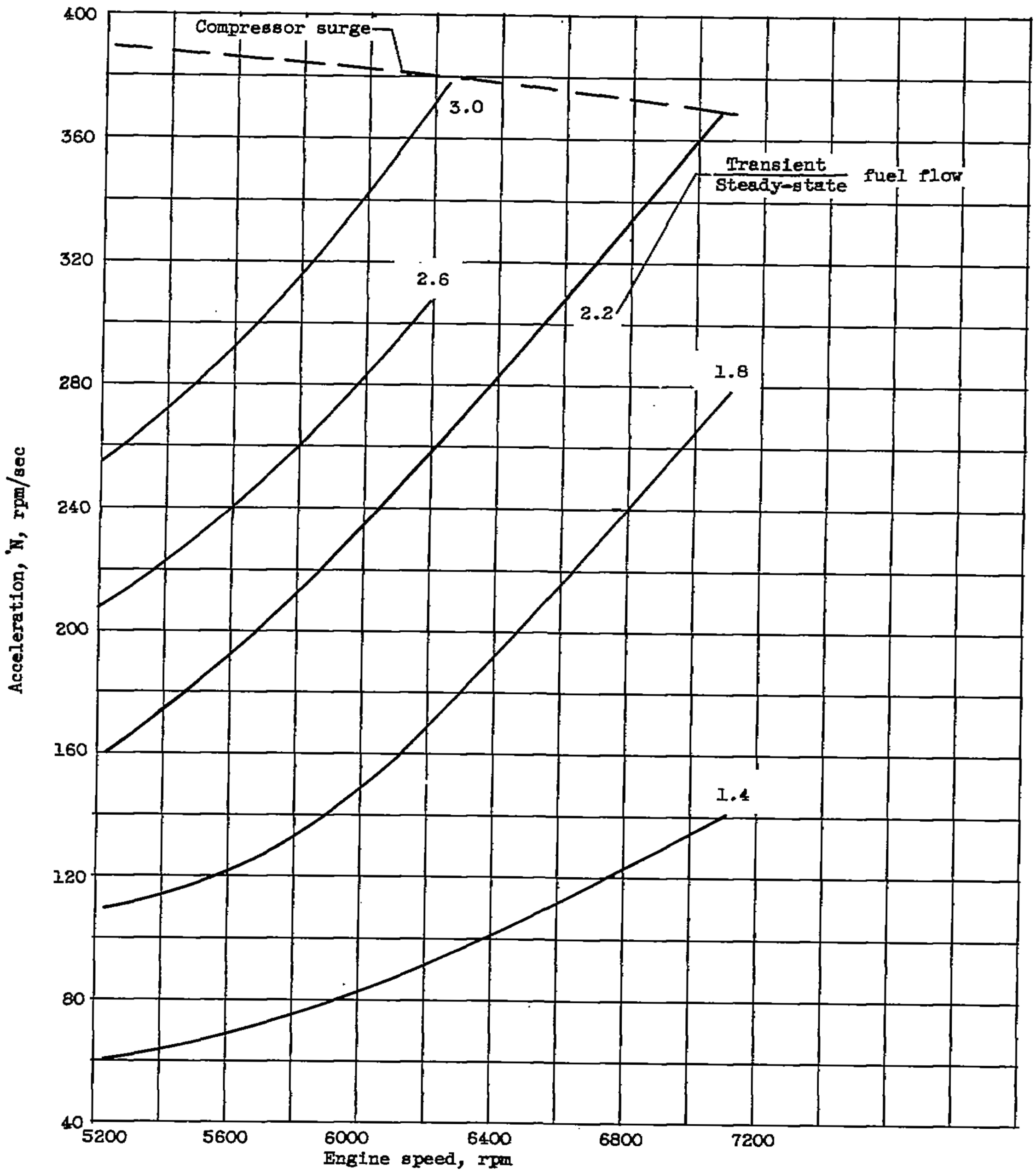

(b) Inlet guide vanes closed.

Figure 4. - Effect of fuel step size on engine acceleration. Altitude, 35,000 ft; flight Mach number, 0.8.

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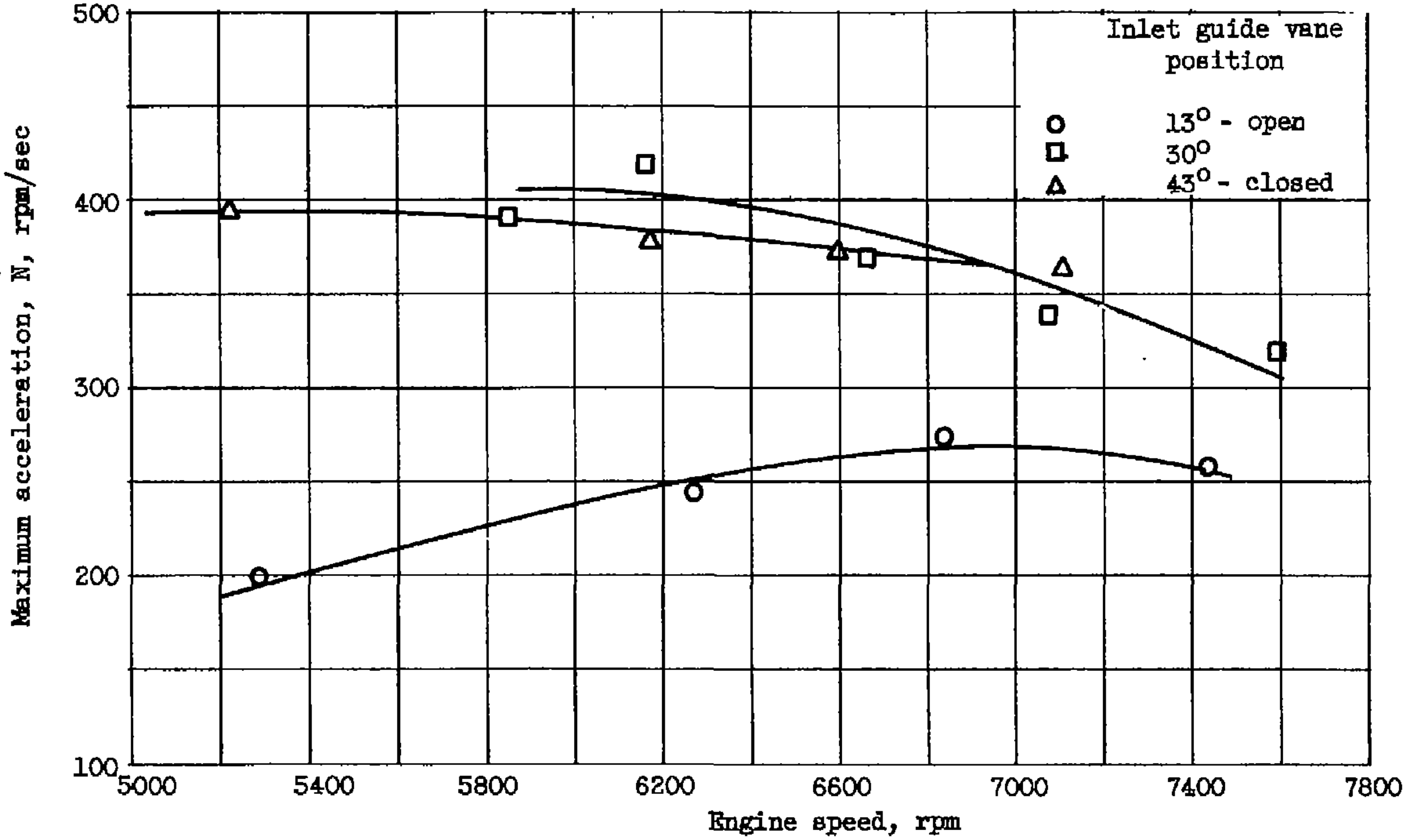

Figure 5. - Effect of inlet guide vane position on maximum acceleration. (Surge limited fuel steps.) Altitude, 35,000 ft; flight Mach number, 0.8.

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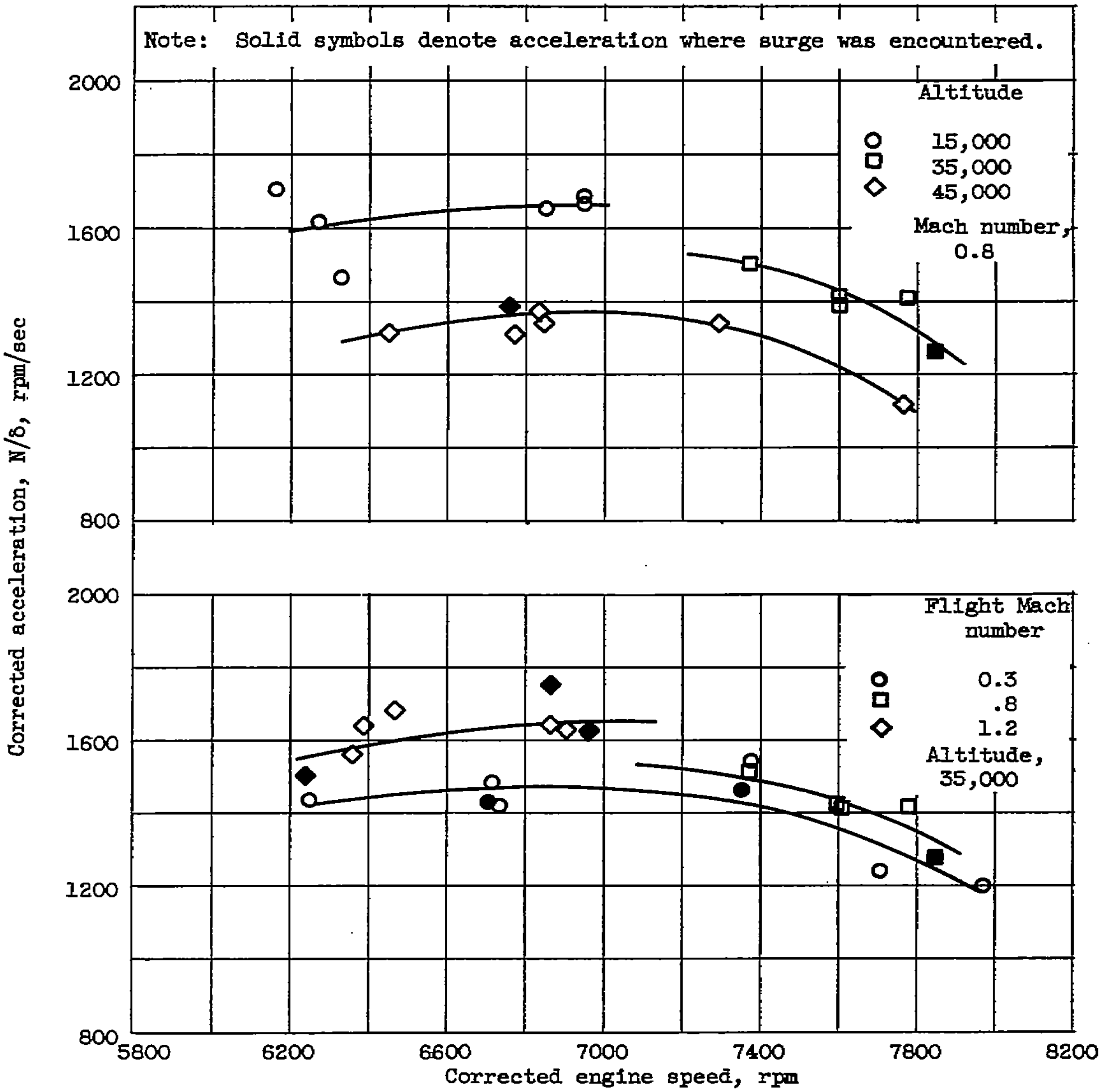

Figure 6. - Effect of changes in flight condition on maximum corrected acceleration. (Surge limited fuel steps.)

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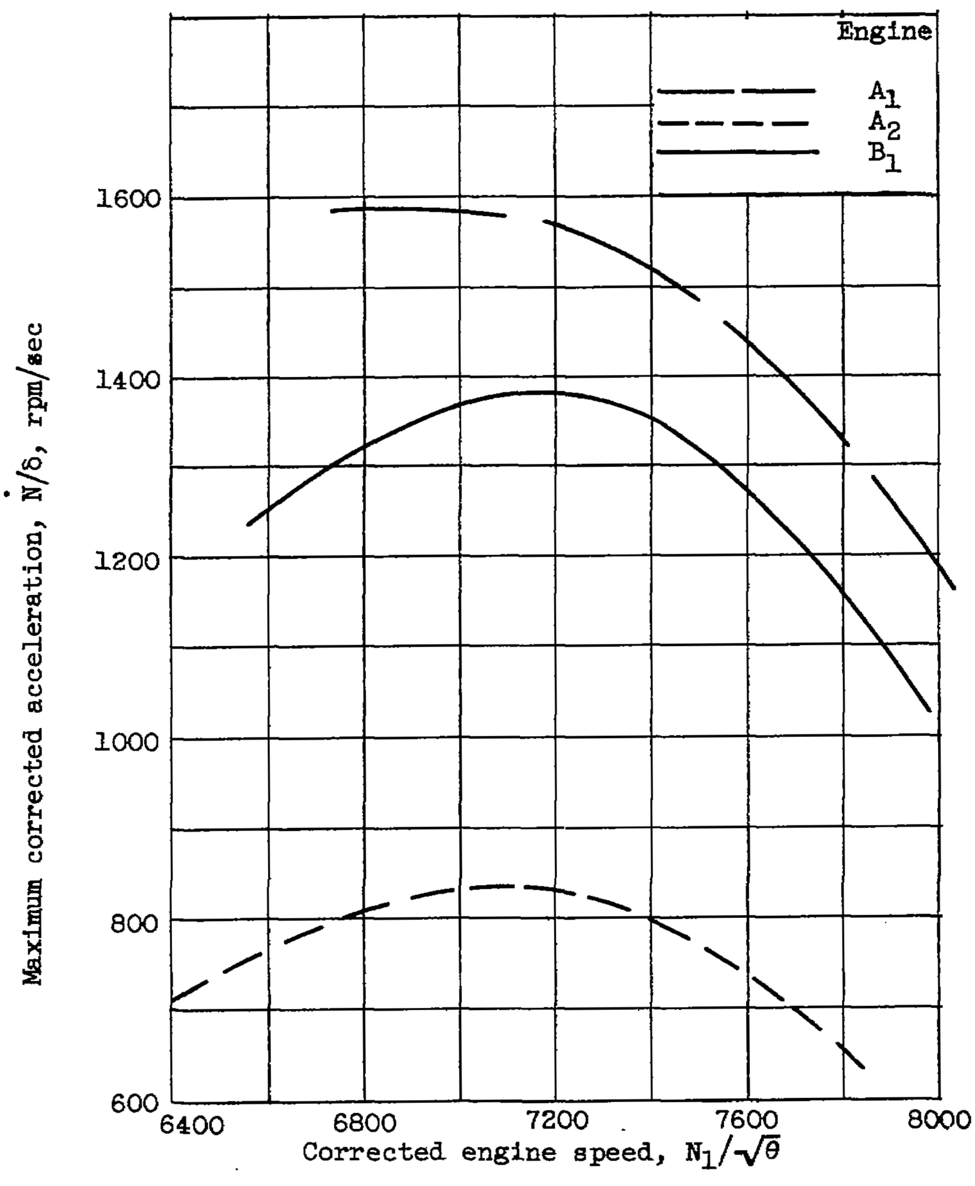

Figure 7. - Maximum acceleration obtained with three turbojet engines. Inlet guide vanes open. Altitude, 35,000 ft; flight Mach number, 0.8.

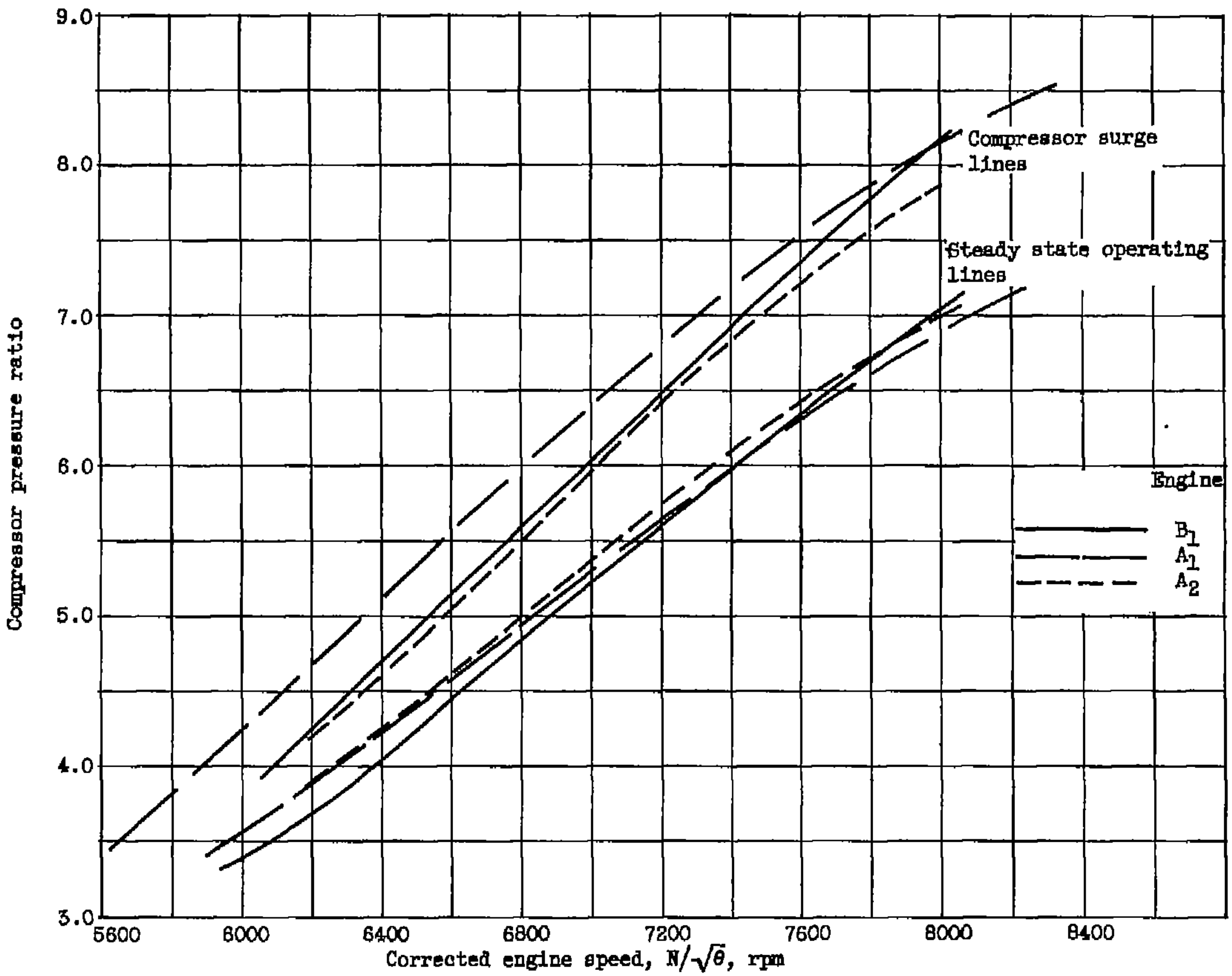

Figure 8. - Surge and steady-state operating lines for three turbojet engines. Altitude, 35,000 ft; flight Mach number, 0.8. Inlet guide vanes, open.

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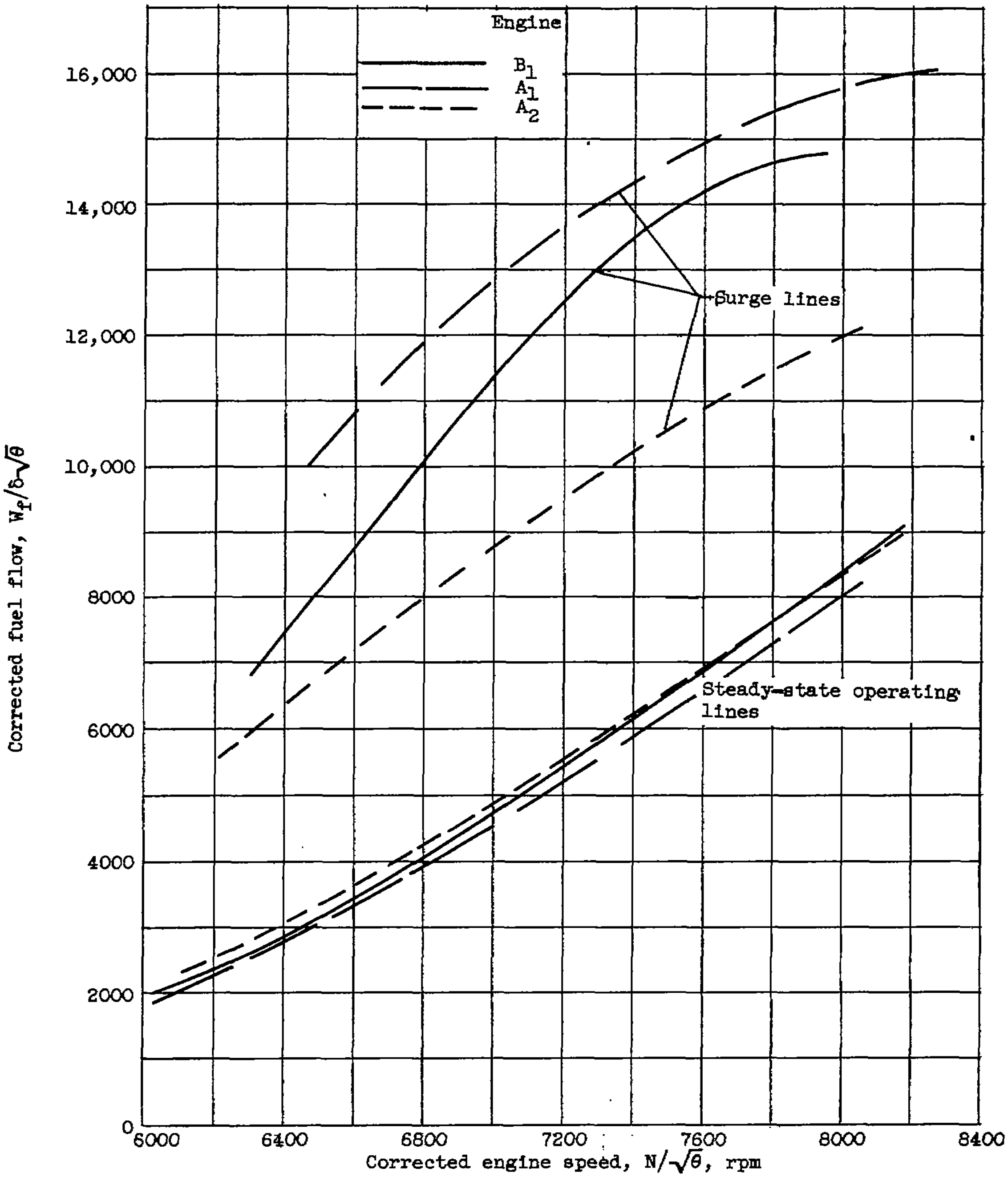

Figure 9. - Variation of surge and steady-state fuel flow, with corrected engine speed for three production engines. Altitude, 35,000 ft; flight Mach number, 0.8. Inlet guide vanes, open.

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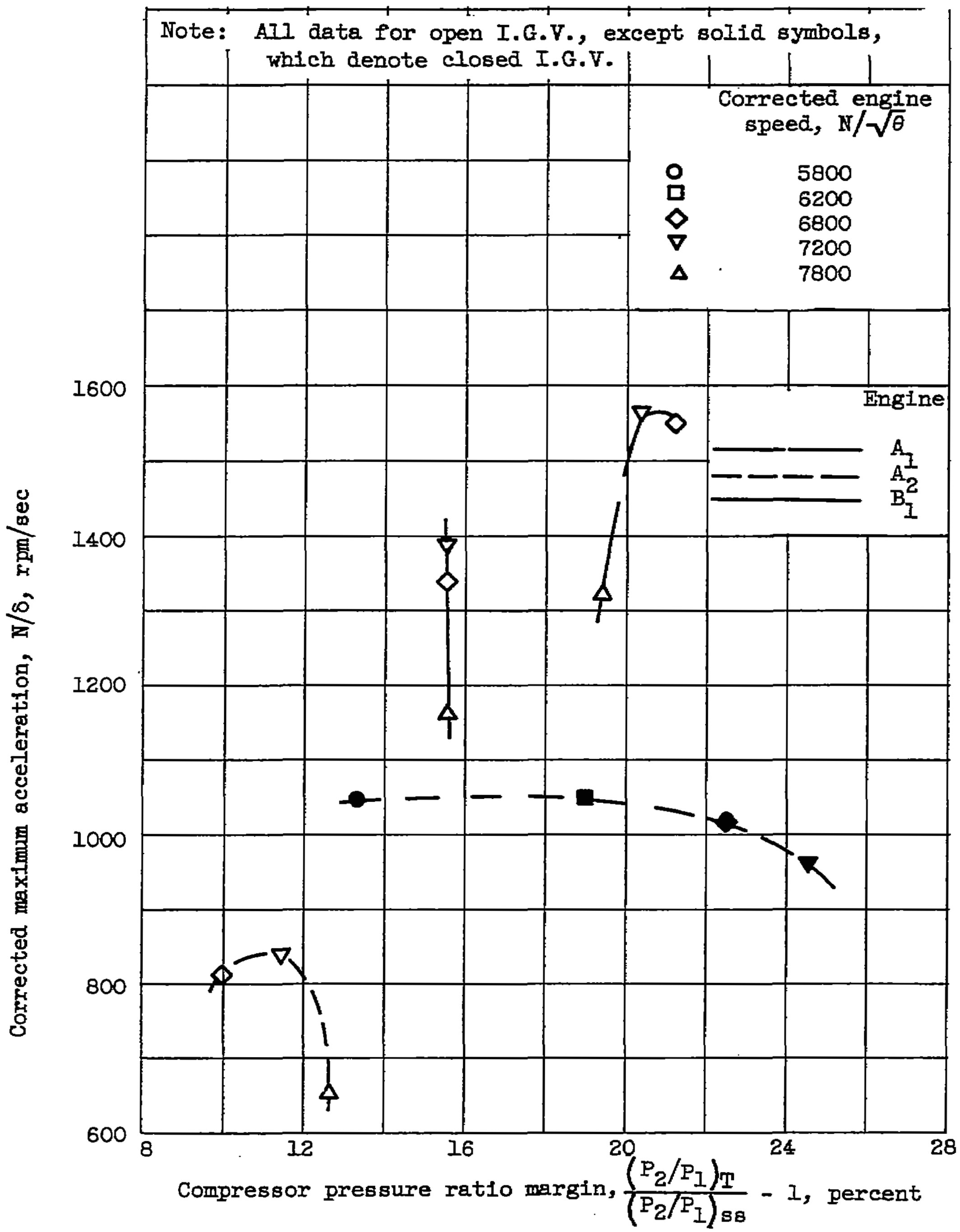

Figure 10. - Variation of maximum acceleration with pressure ratio margin for three turbojet engines. (Surge-limited fuel steps.) Altitude, 35,000 ft; flight Mach number, 0.8.

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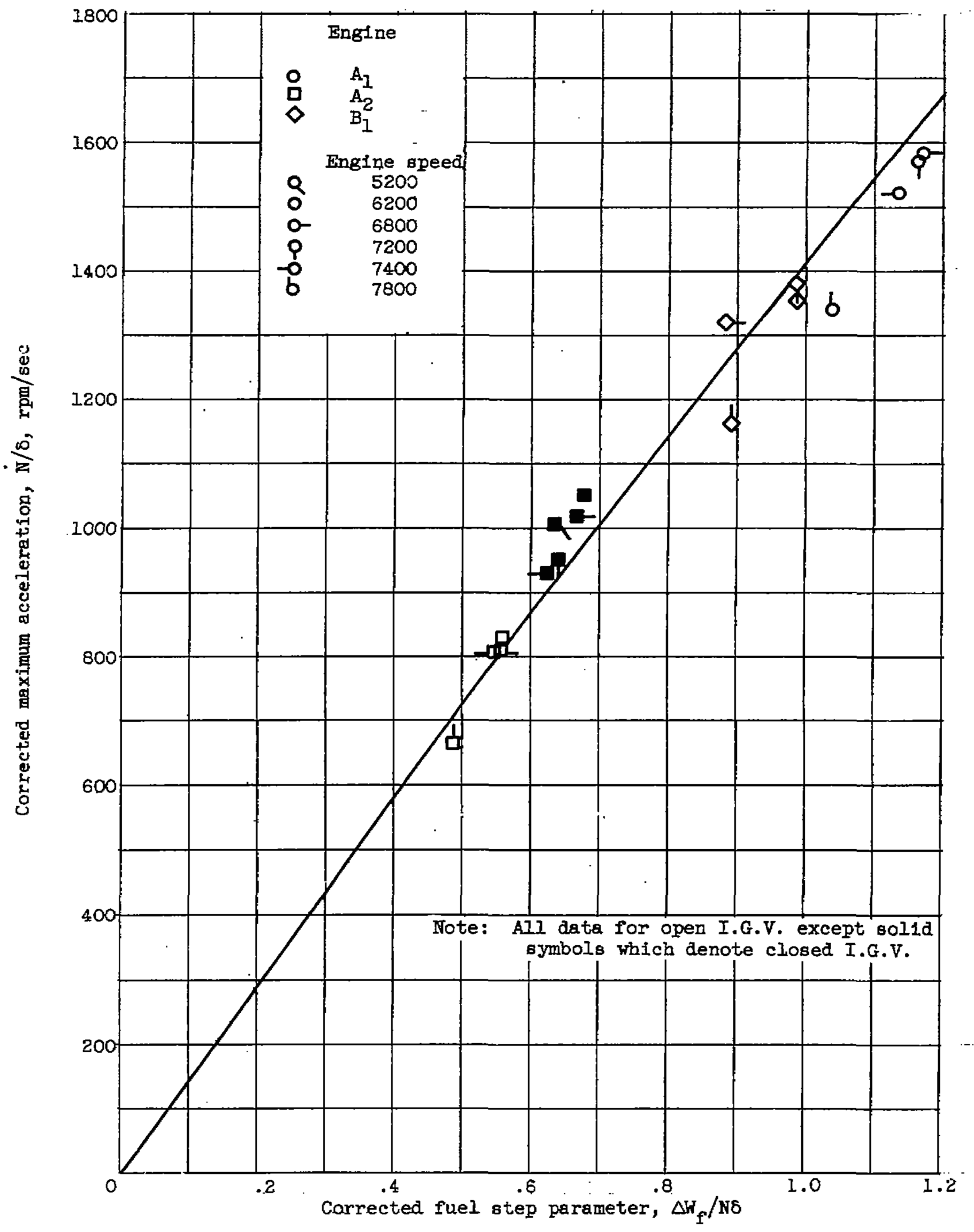

Figure 11. - Variation of maximum acceleration with fuel step parameter for three production engines at various speeds and inlet guide vane settings. Altitude, 35,000 ft; flight Mach number, 0.8. (Surge-limited fuel steps.)

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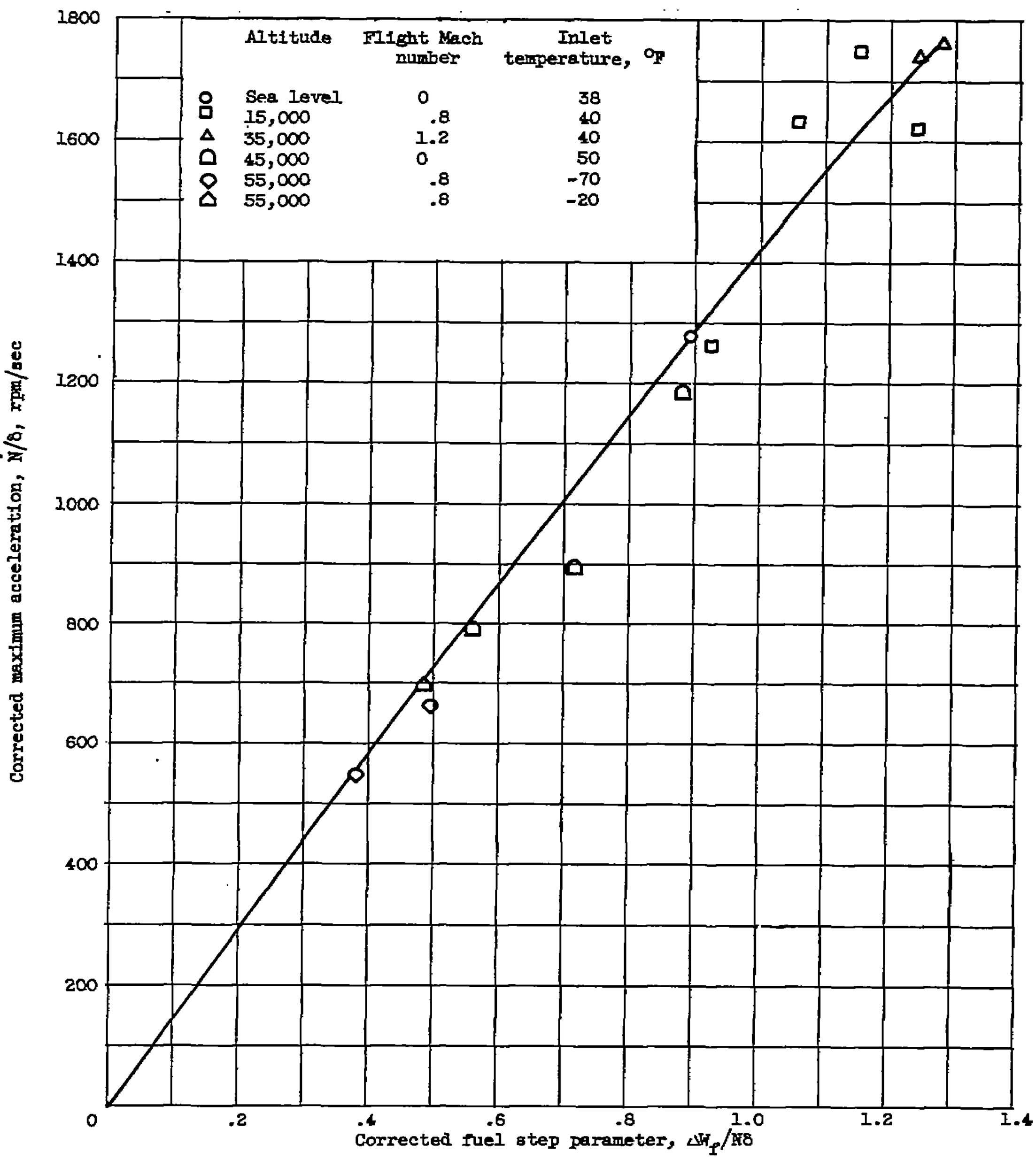

Figure 12. - Variation of maximum acceleration with fuel step parameter for range of inlet conditions. Inlet guide vanes, open. (Surge limited fuel steps.)

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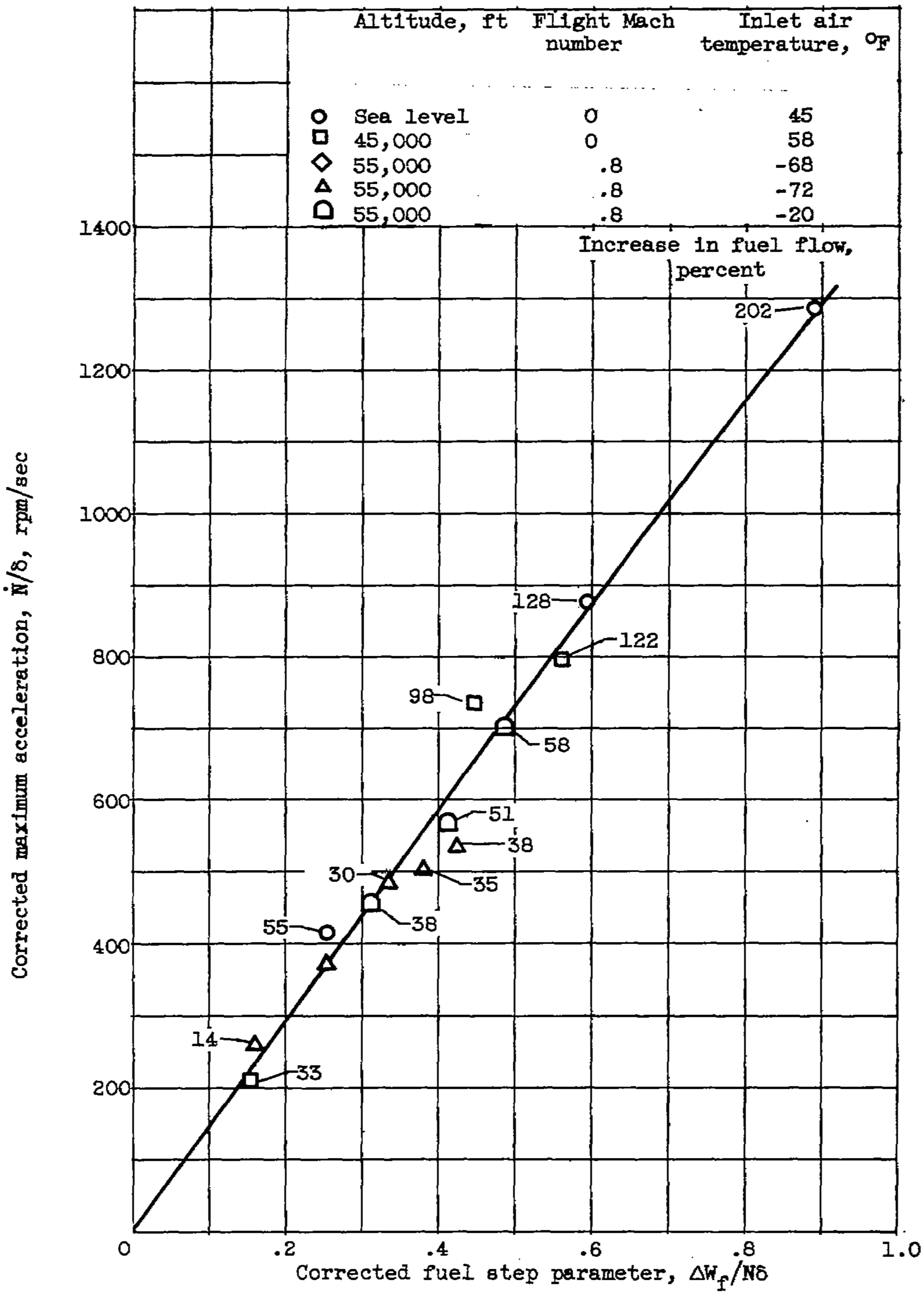

Figure 13. - Variation of acceleration with fuel step parameter for a range of fuel step sizes up to surge fuel flow. Inlet guide vanes, open.

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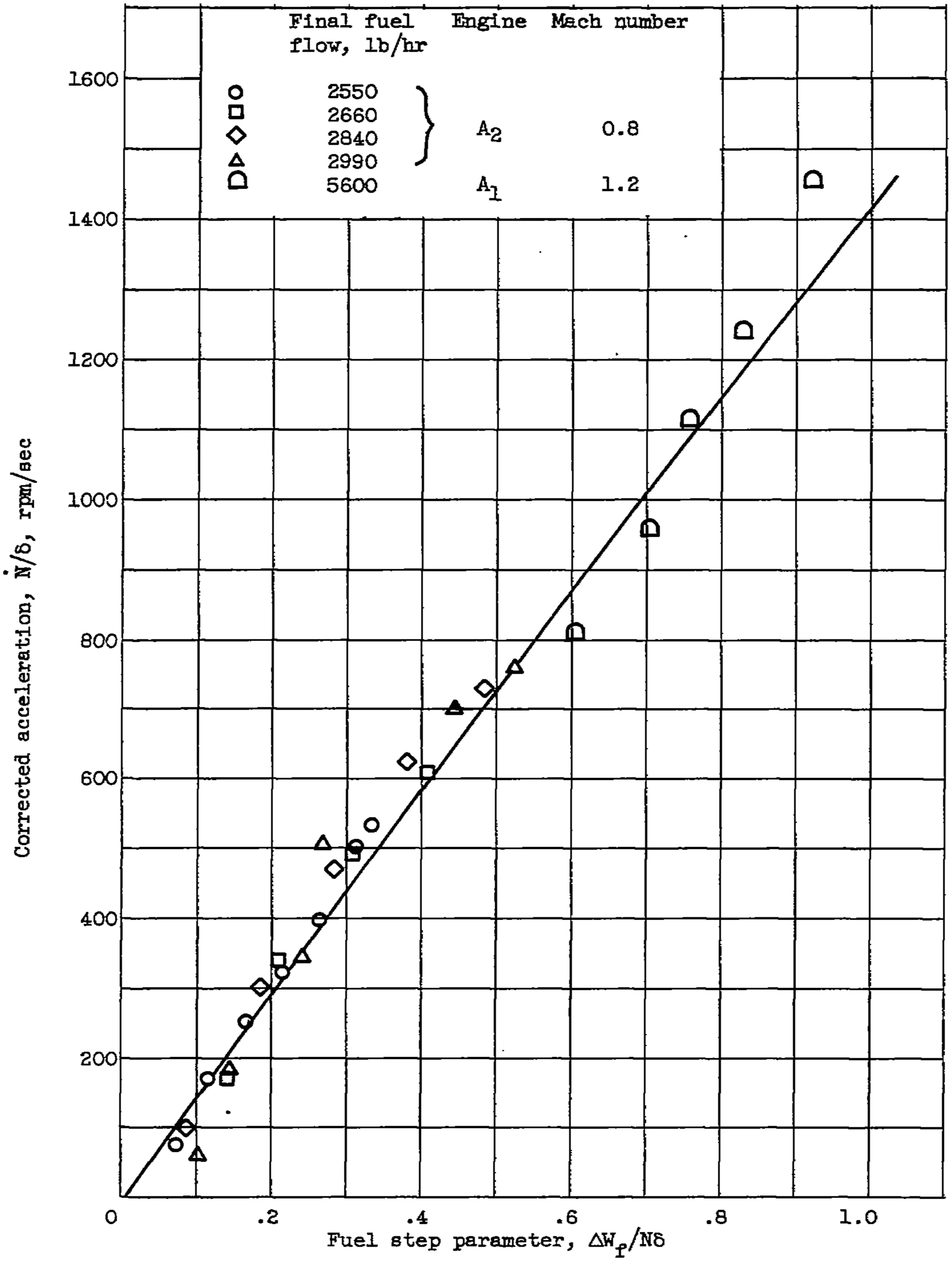

Figure 14. - Acceleration values from time history of step change in engine fuel flow. Inlet guide vanes, open. Altitude, 35,000 feet.

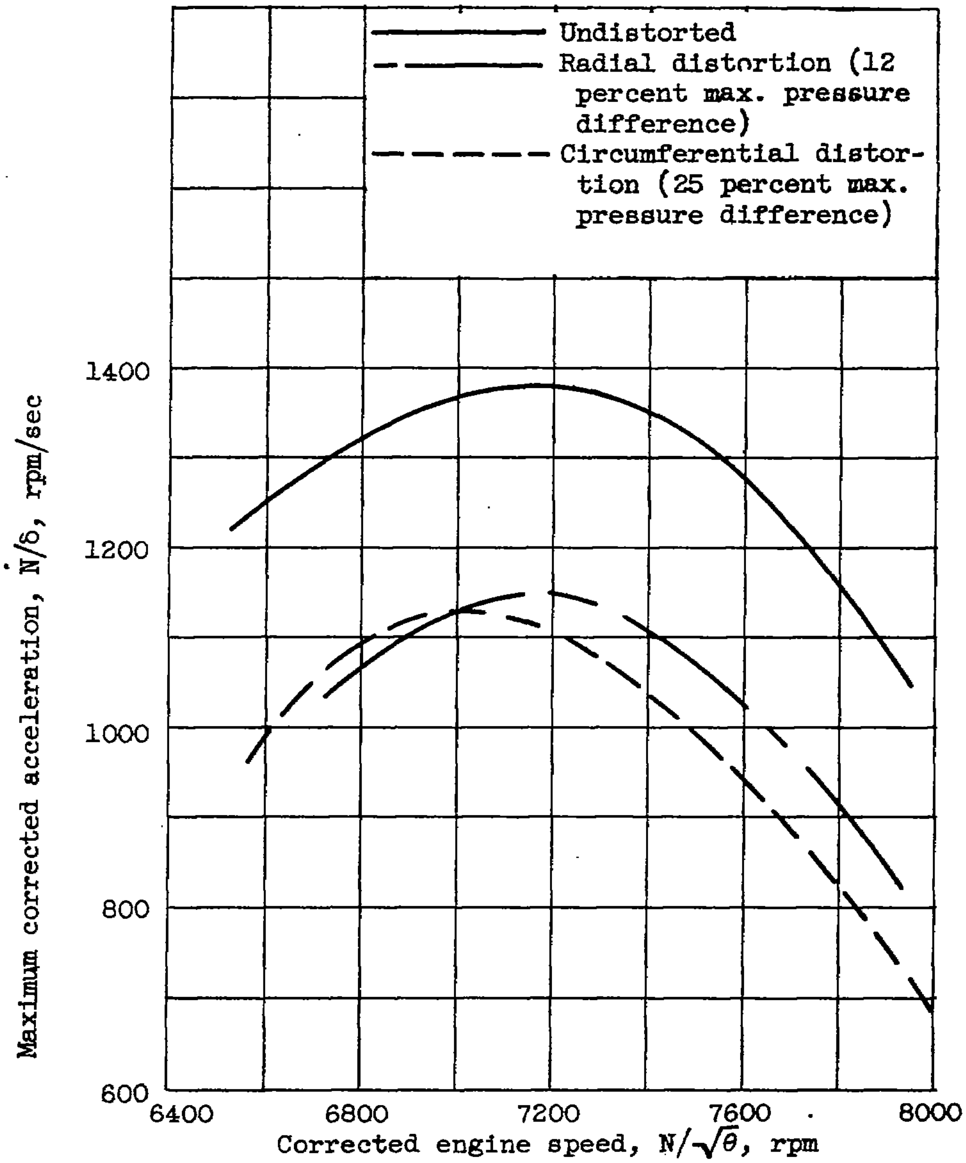

Figure 15. - Effect of inlet air distortion on maximum acceleration. Inlet guide vanes, open. Altitude, 35,000 ft; flight Mach number, 0.8.

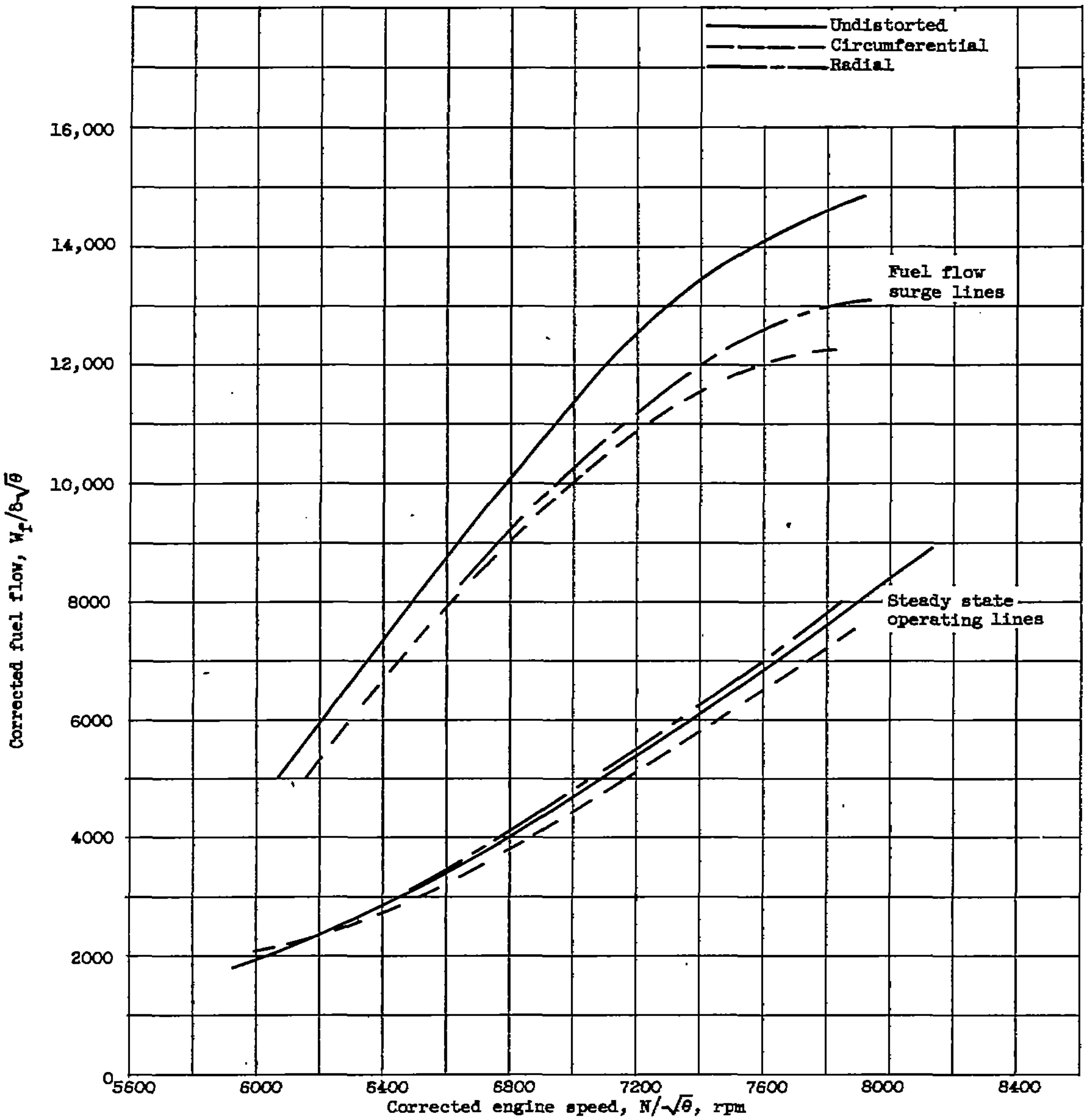

Figure 16. - Effect of inlet distortion on steady state and surge fuel flow lines. Inlet guide vanes, open. Altitude, 35,000 ft; flight Mach number 0.8.

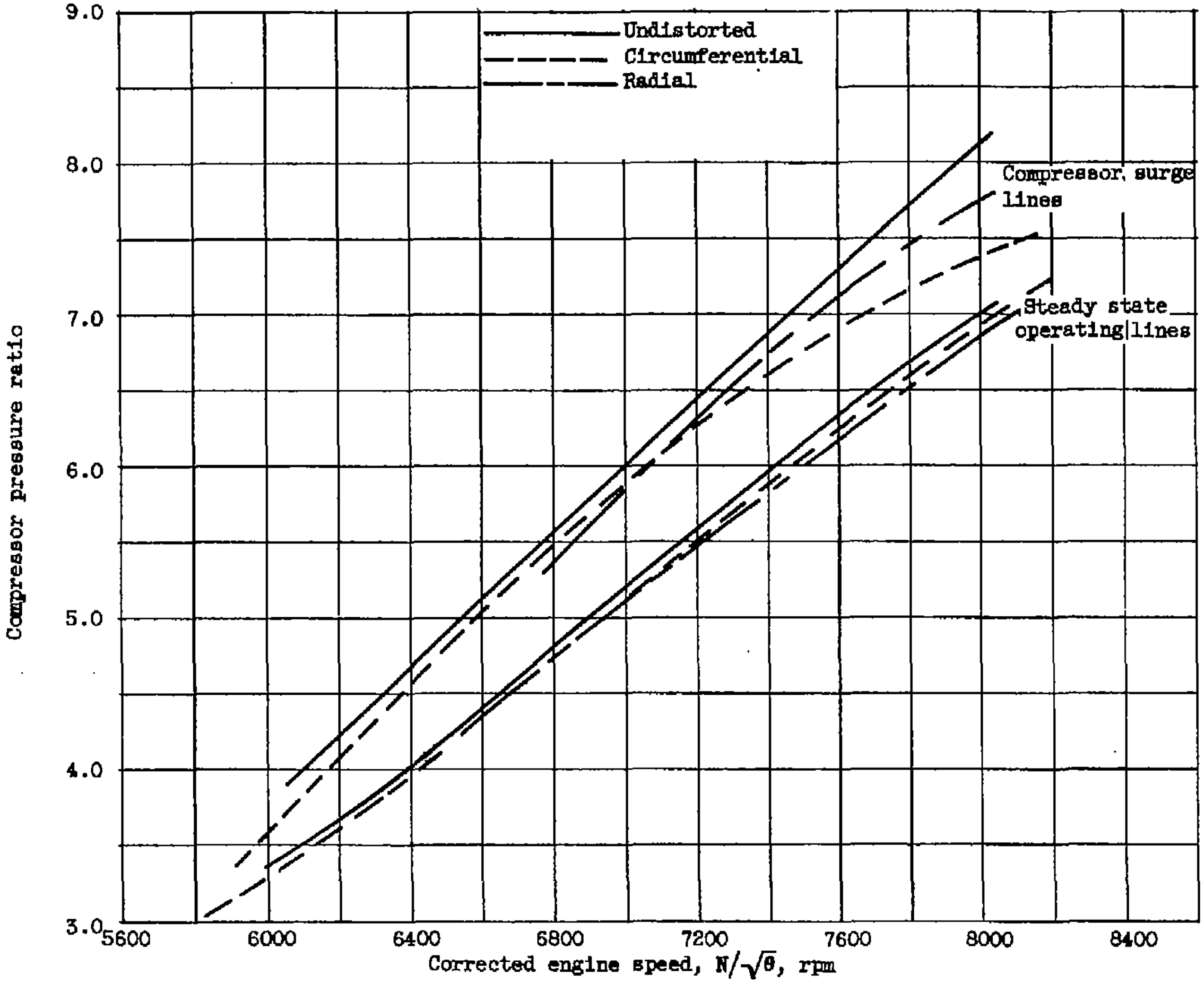

Figure 17. - Effect of inlet air distortion on compressor surge and steady state operating lines. Altitude, 35,000 ft; flight Mach number, 0.8. Inlet guide vanes, open.

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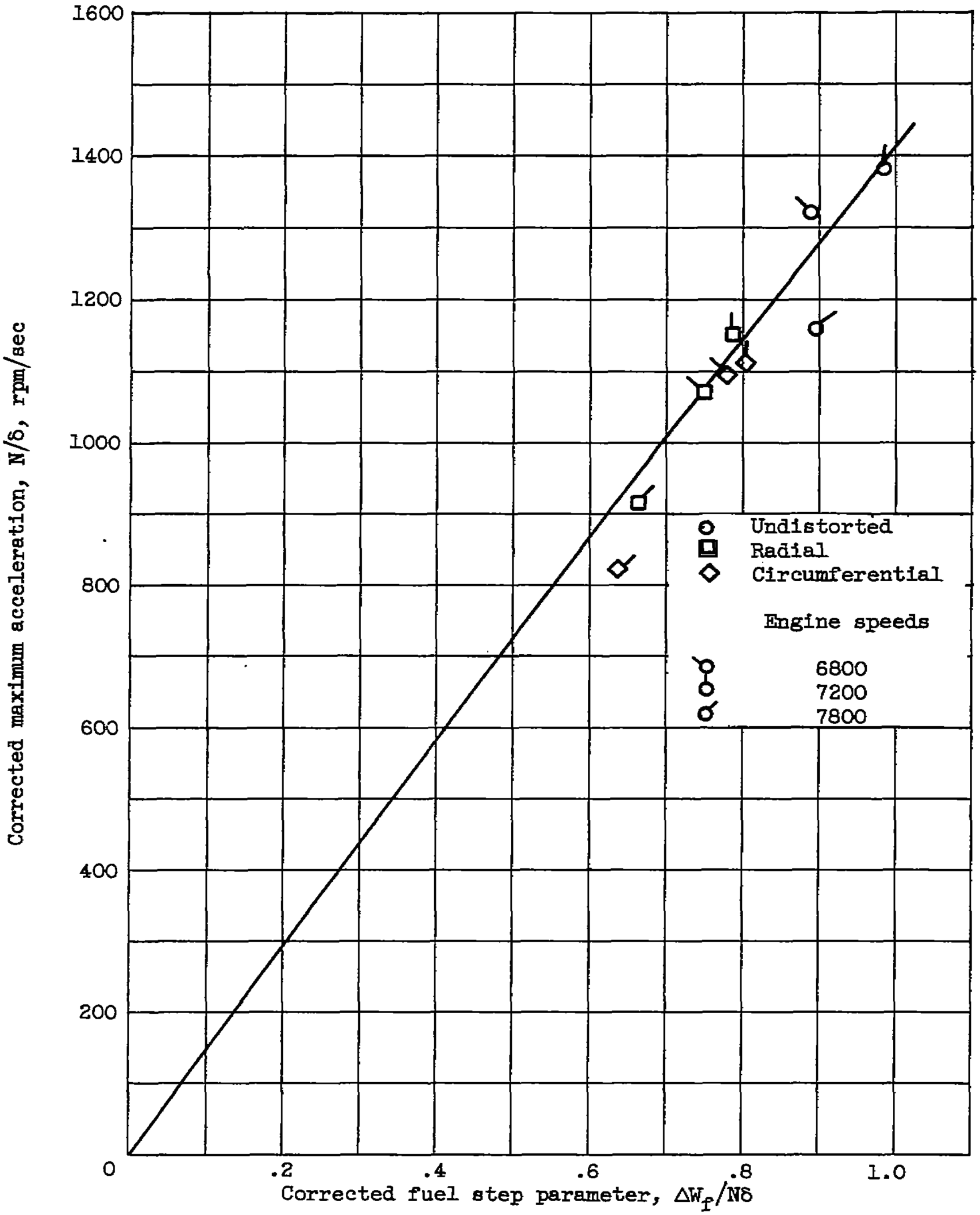

Figure 18. - Variation of maximum acceleration with fuel step parameter for inlet air distortion. Altitude, 35,000 ft; flight Mach number, 0.8. Inlet guide vanes, open.

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